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(54) **Low noise amplifier arrangements**

(57) To obtain optimal operational sensitivity from an amplifier connected to a source of electrical signals, a plurality of amplifiers are interconnected. A method is shown for determining the number of amplifiers (31–1 to 31–N) to be used and whether they should be connected in parallel or series in order to optimize the sensitivity of a given type of amplifier. Accordingly, multiple interconnection of amplifiers may be used in lieu of noise matching transformers to minimize the excess-noise figure of the multiple amplifier circuit. The technique capitalizes on the advances in integrated circuit amplifier design, such as compactness and wideband performance, while providing lower loss and higher reliability through redundancy.

FIG. 3

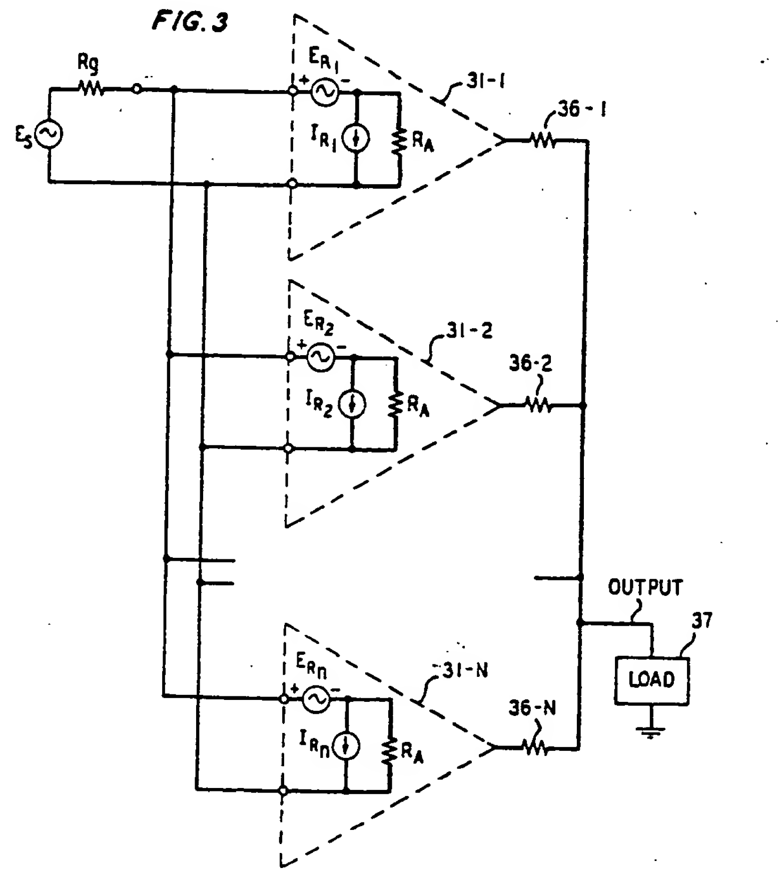


FIG. 1

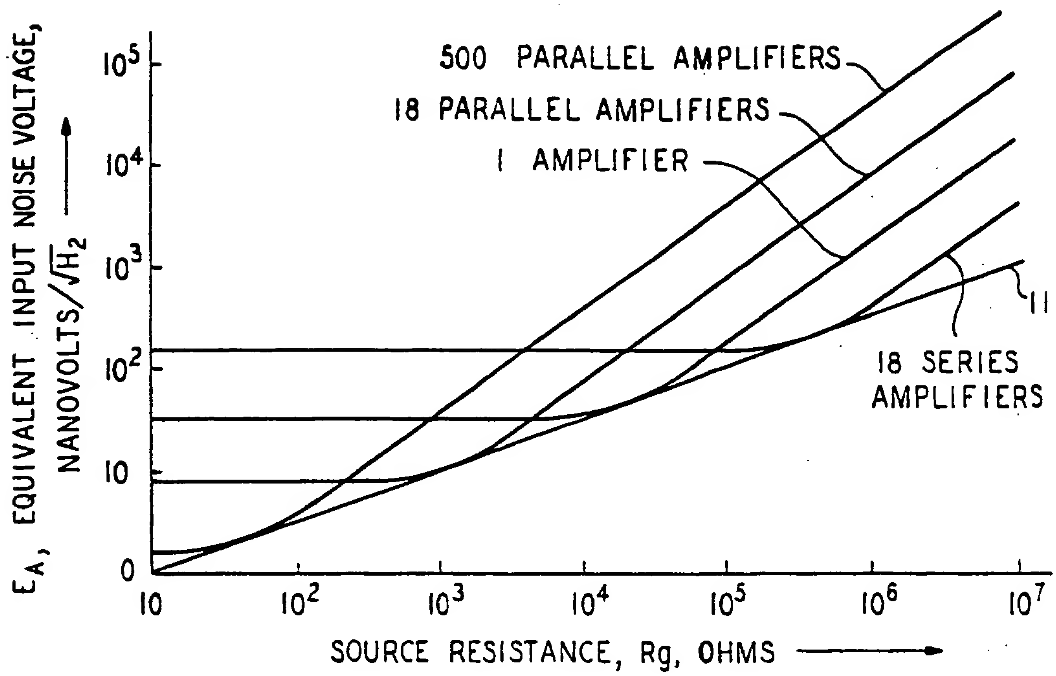

500 PARALLEL AMPLIFIERS
18 PARALLEL AMPLIFIERS
1 AMPLIFIER
11
18 SERIES AMPLIFIERS
E_A, EQUIVALENT INPUT NOISE VOLTAGE, NANOVOLTS/$\sqrt{H_2}$
10^5
10^4
10^3
10^2
10
0
10
10^2
10^3
10^4
10^5
10^6
10^7
SOURCE RESISTANCE, Rg, OHMS

FIG. 2

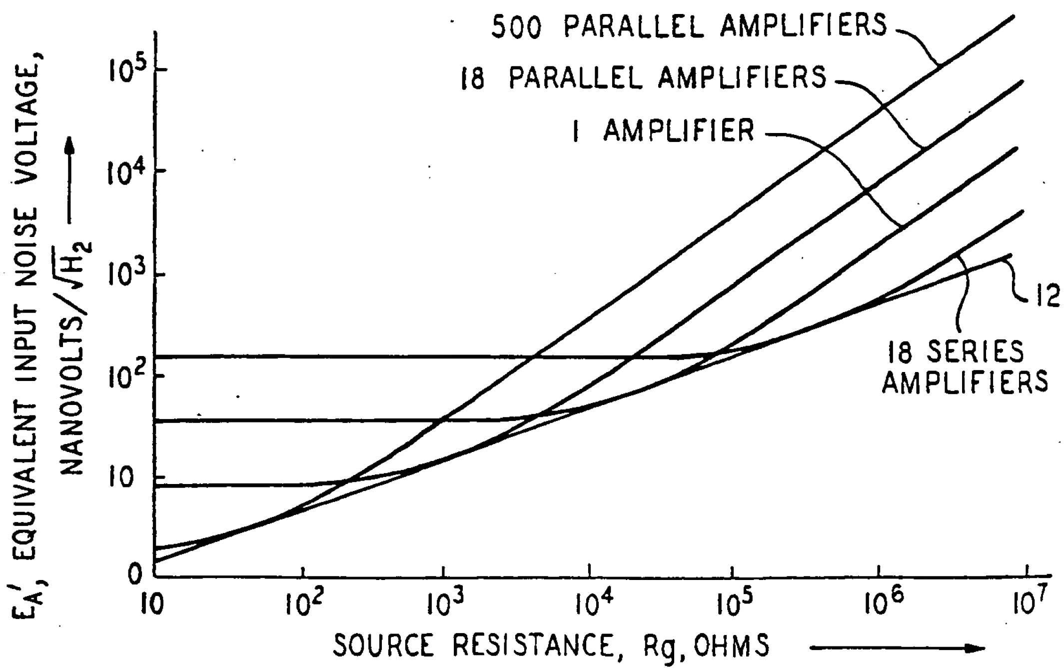
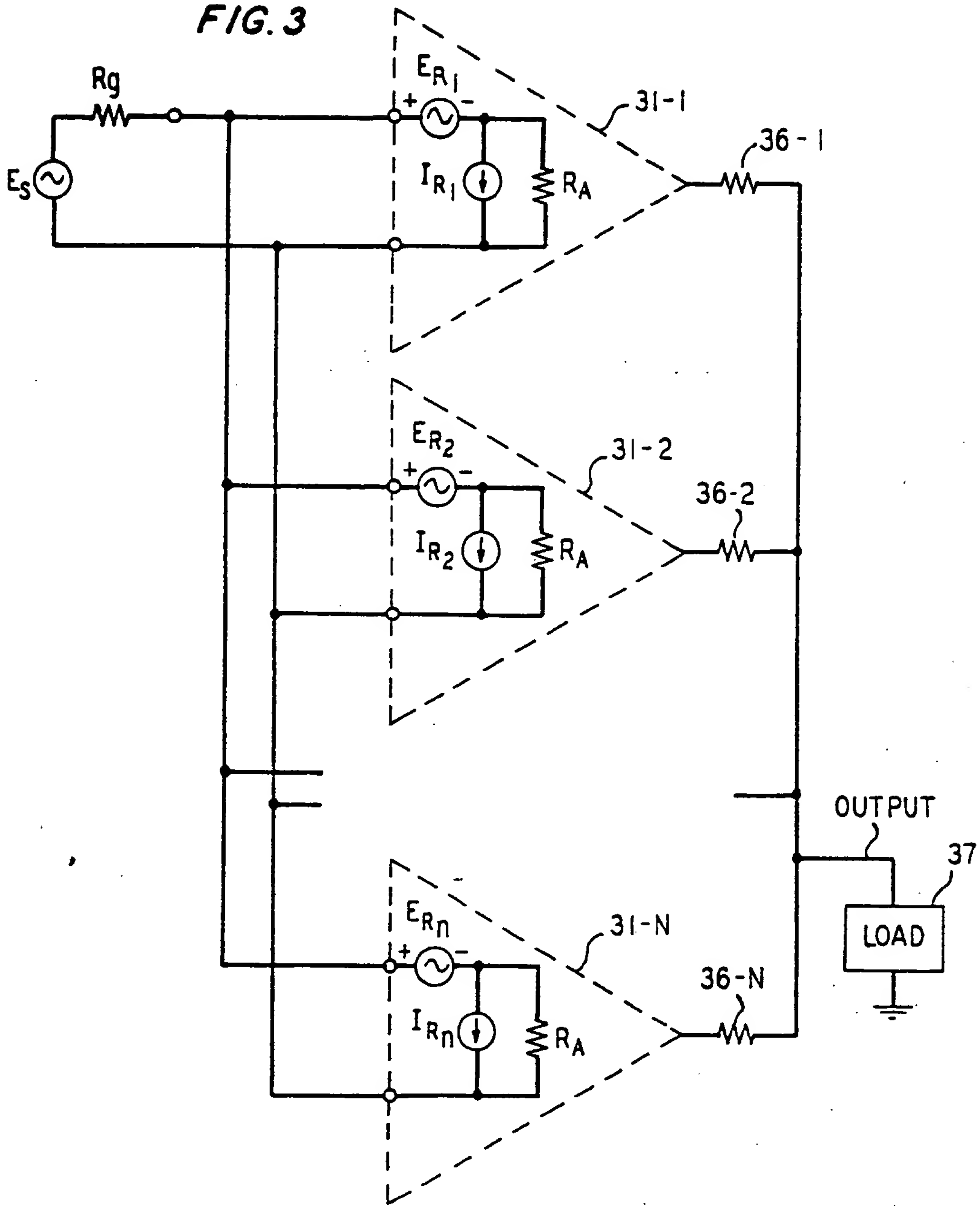
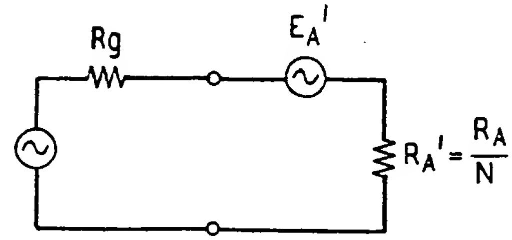

500 PARALLEL AMPLIFIERS
18 PARALLEL AMPLIFIERS
1 AMPLIFIER
12
18 SERIES AMPLIFIERS
E_A', EQUIVALENT INPUT NOISE VOLTAGE, NANOVOLTS/$\sqrt{H_2}$
10^5
10^4
10^3
10^2
10
0
10
10^2
10^3
10^4
10^5
10^6
10^7
SOURCE RESISTANCE, Rg, OHMS

FIG. 3



Rg
E_S
E_{R_1}
+
-
I_{R_1}
R_A
31-1
36-1
E_{R_2}
I_{R_2}
31-2
36-2
E_{R_n}
I_{R_n}
31-N
36-N
OUTPUT
37
LOAD

FIG. 4



Rg
E_A'
$R_A' = \frac{R_A}{N}$

FIG. 5

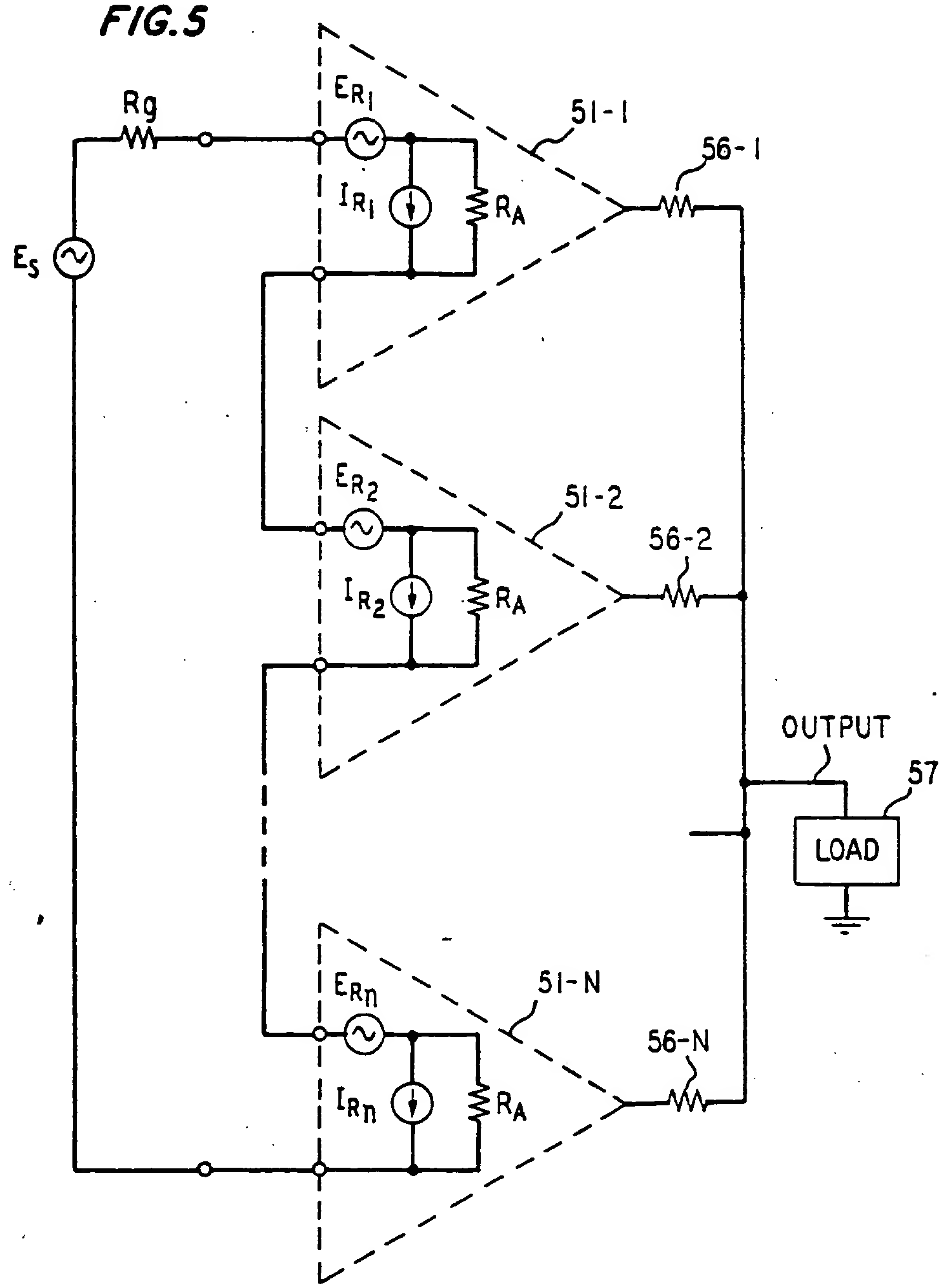
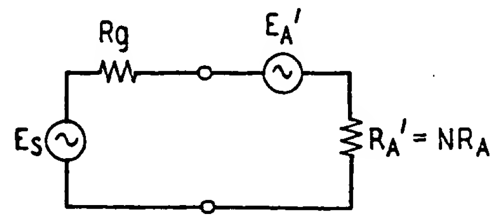

Rg
E_{R_1}
51-1
56-1
E_S
I_{R_1}
R_A
E_{R_2}
51-2
56-2
I_{R_2}
R_A
OUTPUT
57
LOAD
E_{R_n}
51-N
56-N
I_{R_n}
R_A

FIG. 6


Rg
E_A'
E_S
$R_A' = NR_A$

SPECIFICATION

Low noise amplifier arrangements

This invention relates to low noise amplifier arrangements and, more particularly, to a method and arrangement for improving the signal-to-noise performance of such arrangements.

A well-known limitation on the operational sensitivity of amplifiers for low signal applications is their characteristic noise performance. The general approach for minimizing the effect of noise in applications involves matching the "noise impedance" of an amplifier to the output impedance of the signal source to obtain the maximum benefit from the input signal. This technique is commonly referred to as noise matching. Typically, practical applications dictate the value of the impedance or resistance, of the signal source and the "noise resistance" of the amplifier should be matched thereto.

At low video frequencies, transformers may be used to provide the noise matching but they are usually bulky and likely to pick up the noise. At higher frequencies, transformers tend to be lossy in addition to being bulky. Transmission line impedance transformers for operation at microwave frequencies are lossy and are unsuitable for applications requiring compact design. Since all transformers are somewhat frequency dependent, they tend to limit the useful bandwidth of the amplifiers in which they are used.

Other applications use so-called, simulated low-noise resistors for matching the "noise impedance" of an amplifier to the signal source. Although this eliminates the impedance matching transformer, such an approach introduces an additional noise source without a direct benefit in amplifier gain, i.e. that which is inherent in the amplifier of the simultated resistor. Furthermore, due to stablity considerations of such simulators, there is only a limited range available for matching impedances.

According to one aspect of the present invention there is provided a method of providing low noise amplification of a source of electrical signals including a predetermined source resistance R_g, by utilizing a plurality of like amplifiers, the method comprising determining for each amplifier a rms noise voltage E_R and a rms noise current I_R, determining the ratio E_R/I_R, determining if R_g is greater or less than the ratio E_R/I_R, and where R_g is less than E_R/I_R connecting a plurality of N of the like amplifiers in parallel where N is approximately equal to the quantity $E_R/(I_RI_g)$, and where R_G is greater than E_R/I_R connecting a plurality N′ of the like amplifiers in series, where N′ is approximately equal to the quantity $(I_RR_g)/E_R$.

According to another aspect of the present invention there is provided low noise amplifier arrangement for providing amplified electrical signals from a source of electrical signals including a predetermined source resistance R_g, the arrangement comprising a plurality of like amplifiers which are connected together, each amplifier including a predetermined rms noise voltage E_R and a predetermineo rms noise current I_R, and in which a plurality of N like amplifiers are connected in parallel, wherein N is approximately equal to the quantity $E_R/(I_RR_g)$, for R_g less than E_R/I_R and a plurality of N′ like amplifiers are connected in series, where N′ is approximately equal to the quantity $(I_R/R_g)/E_R$, for R_g greater than E_R/I_R.

Broadly, in one respect the present invention takes the form of a low noise amplifier arrangement wherein a plurality of interconnected amplifiers without using matching hybrids or transformers, is able to provide increased operational sensitivity over that provided by a single amplifier.

A feature of the inventive arrangement is that operational sensitivity is increased by circuit replication of amplifiers which capitalizes on the lower cost and miniaturization of amplifiers provided by advances in integrated circuit technology.

The above-mentioned and other features and objects of the present invention will become more apparent by reference to the following detailed description which should be read in conjunction with the accompanying drawings, in which:

Figure 1 is a graph illustrating optimal noise performance for various amplifier combinations wherein the noise current source and noise voltage source inherent to the amplifier are uncorrelated with each other.

Figure 2 is a similar chart to Fig. 1 wherein the noise voltage source and noise current source of the amplifiers used are perfectly correlated.

Figure 3 illustrates the connection of a plurality of amplifiers with their inputs in parallel.

Figure 4 depicts the equivalent impedance relationship produced by Fig. 3.

Figure 5 depicts a plurality of amplifiers connected so that their inputs are serial.

Figure 6 is the equivalent circuit of the impedance relationship present in Fig. 5.

For purposes of the ensuing discussion, the noise performance of an amplifier is represented by an rms noise voltage source, E_R, and an rms noise current source I_R present at the input of an amplifier. These noise sources may be correlated or uncorrelated with the latter thought to occur most frequently. Each source of electrical signals includes a source resistance R_g. The impedance relationship between the internal noise sources of the amplifier and the source resistance

determines the lower limit on the operational sensitivity of an amplifier. Conventionally an impedance matching transformer couples a signal source to the amplifier and is used to increase the operational sensitivity of the amplifier by reducing its excess noise figure.

The total equivalent input noise voltage, E_A, of an amplifier is a function of the source resistance R_g. For example, in the case of a detector diode source, R_g is the sum of two quantities. R_s (the series spreading resistance) is the first quantity plus R_B (the barrier resistance of an ideal diode). The equivalent input noise voltage may be expressed as:

$$E_A = \begin{cases} \sqrt{E_R^2 + I_R^2 R_g^2}\ ; & E_R \text{ and } I_R \text{ uncorrelated,} \\ E_R + I_R R_g; & E_R \text{ and } I_R \text{ perfectly correlated,} \end{cases} \qquad (1)$$

where E_R and I_R are rms equivalent noise voltage and current sources, respectively, reflected to the input and are approximately independent on the source resistance. When a transformer is used to match the source to the input of an amplifier, E_A may be calculated with

$$E_A = \sqrt{E_R^2 + \frac{I_R^2(R_B + R_S)^2}{n^4}} \qquad (2)$$

where n is the turn ratio of the transformer. The rms equivalent input noise is

$$E'_A = nE_A = \begin{cases} [nE_R]^2 + \left[\dfrac{I_R R_g}{n}\right]^2; & E_R \text{ and } I_R \text{ uncorrelated,} \\ nE_R + \dfrac{I_R R_g}{n}; & E_R \text{ and } I_R \text{ perfectly correlated.} \end{cases} \qquad (3)$$

The value of n which minimizes E_A' in Equation (3) is

$$nopt = \sqrt{\frac{I_R R_g}{E_R}}. \qquad (3a)$$

For this optimum turns ratio the rms equivalent input noise is

$$E'_A = \begin{cases} 2\sqrt{E_R I_R R_g}; & E_R \text{ and } I_R \text{ uncorrelated,} \\ 2\sqrt{E_R I_R R_g}; & E_R \text{ and } I_R \text{ perfectly correlated.} \end{cases} \qquad (3b)$$

In such a case the excess-noise figure, $F-1$, is found by

$$F - 1 = \frac{(E'_A)^2}{4kTBR_g}, \qquad (4)$$

where k is Boltzmann's constant, T is the temperature in degrees Kelvin, and B is the bandwidth measured in Hz. Thus, for each source resistance, R_g, minimizing the excess noise figure is synonymous with minimizing E'_A.

Fig. 1 represents the impedance relationship of the input noise voltage E'_A to the source resistance. The straight line 11 represents the optimum conventional arrangement wherein an idealized transformer having a continuously adjustable turns ratio provides optimum coupling between a given amplifier "noise impedance" and a range of impedances for the signal source. Of course, such a transformer does not exist or, at least would be difficult to realize in practical circuit arrangements. However. it does illustrate the optimum operational sensitivity which can be achieved from an amplifier by minimizing the effect of its equivalent input noise for various values of source resistance.

The curved lines or characteristics of amplifiers whose knees are tangential to line 11 represents various combinations of pluralities of amplifiers whose internal noise voltage source and noise current source are uncorrelated with each other. The noise voltage source, E_R, has a value of $35nV/\sqrt{Hz}$ and noise current source, I_R, has a value of $1.75pA/\sqrt{Hz}$. Accordingly, the selection of the appropriate number of amplifiers in either parallel or serial arrangements is able to obtain optimum operational sensitivity throughout a wide range of source resistance

values.

Fig. 2 illustrates a similar relationship wherein line 12 is the optimization line when the noise voltage source and noise current sources have the same values as in Fig. 1, but are perfectly correlated. In either case, connection of the appropriate number of amplifiers together whether in series or in parallel is able to achieve maximum operational sensitivity throughout a large range of values for the source resistance.

Fig. 3 is a circuit which provides parallel interconnection of a plurality of amplifiers 31–1 through 31N, each of the amplifiers 31 being essentially identical to each other, the input of the amplifier circuit is driven by a voltage source E_s having a source resistance R_g. Each amplifier contains an internal noise voltage source and noise current source connected to drive the input impedance of the amplifier R_A. The amplifier outputs are connected together in a star configuration by resistors 36–1 to 36–N, so that each amplifier contributes equally to drive load 37.

Fig. 4 is an equivalent circuit symbolically representing the impedance relationship present in Fig. 3. The combined effect of the parallel connection of amplifiers is represented by the serial connection of E'_A and the reflected impedance R'_A equal to

$$\frac{R_A}{N}.$$

Since R_A is predetermined for a given type of amplifier, the value of R'_A may be determined simply by parallelling the input of the appropriate number of individual amplifiers. Accordingly, the input impedance of the overall amplifier is reduced by dividing the individual input impedance of a single amplifier by the number of amplifiers connected in parallel. This arrangement is chosen when the source resistance R_g is less than

$$\frac{E_R}{I_R}.$$

The number of amplifiers N is an integer in practice determined by $N = E_R/(I_R R_g)$.

Fig. 5 is a circuit diagram for connecting the input of N′ individual amplifiers together serially. Again, each of amplifiers 51–1 through 51–N′ are essentially identical to each other. The outputs of each of amplifiers 51 are again connected in star configuration to drive load 57 via individual resistors 56–1 through 56–N′.

Fig. 6 is a circuit diagram depicting the equivalent impedance relationship represented by the serial connection of N′ amplifiers. In this arrangement, the equivalent input impedance R'_A is the product of the number of amplifiers N′ times R_A. The serial interconnection is selected when R_g is greater than

$$\frac{E_R}{I_R}$$

where the number of amplifiers is determined by $N' = (I_R R_g)/E_R$.

With respect to available integrated circuit amplifiers, multiple interconnection of such amplifiers in parallel or series will provide optimal operational sensitivity over a range of various source resistances. When bipolar integrated amplifiers are used which typically have a relatively low input "noise impedance", the inventive principles may be employed by connecting their inputs serially together. For field effect transistor amplifiers, including junction field effect transistors, whose input "noise impedance" is relatively high, parallel interconnection of a plurality of amplifier inputs in accordance with the inventive principles may be utilized for obtaining optimal operational sensitivity for source resistances that are low with respect to the input "noise impedance" of an individual amplifier. In other cases, the inventive technique may provide those in the art with the option of using the type of amplifier which is most advantageous in a particular application.

In all cases, it is to be understood that the embodiments described in the foregoing are merely illustrative of but a few of many possible specific embodiments which represent applications of the principles of the present invention. In a particular application, for example, it may be desirable to use both a series and parallel combination of amplifiers. Other methods of connecting the amplifier outputs can be used; e.g., multiport power combiners, or an array of hybrid couplers. Accordingly, numerous and varied other arrangements may be readily devised in accordance with these principles by those skilled in the art without departing from the spirit and scope of the invention.

CLAIMS

1. A method of providing low noise amplification of a source of electrical signal including a predetermined source resistance R_g, by utilizing a plurality of like amplifiers, the method comprising determining for each amplifier a rms noise voltage E_R and a rms noise current I_R, determining the ratio E_R/I_R, determining if R_g is greater or less than the ratio E_R/I_R, and, where R_g is less than E_R/I_R connecting a plurality N of the like amplifiers in parallel where N is approximately equal to the quantity $E_R/(I_R R_g)$, and where R_G is greater than E_R/I_R connecting a plurality N' of the like amplifiers in series, where N' is aproximately equal to the quantity $(I_R R_g)/E_R$.

2. A low noise amplifier arrangement circuit for providing amplified electrical signals from a source of electrical signals including a predetermined source resistance R_g, the arrangement comprising a plurality of like amplifiers which are connected together, each amplifier including a predetermined rms noise voltage E_R and a predetermined rms noise current I_R, and in which a plurality of N like amplifiers are connected in parallel, where N is approximately equal to the quantity $E_R/(I_R R_g)$, for R_g less than E_R/I_R and a plurality of N' like amplifiers are connected in series, where N' is approximately equal to the quantity $(I_R R_g)/E_R$, for R_g greater than E_R/I_R.

3. An arrangement as claimed in claim 2, comprising output means for providing a common output node, the output means being resistively coupled individually to each of the outputs of the plurality of amplifiers.

4. An arrangement as claimed in claim 2, in which the plurality of N like amplifiers have their inputs connected in parallel while their outputs are individually resistively coupled to an output node.

5. An arrangement as claimed in claim 2, in which the plurality of N' like amplifiers have their inputs serially connected and output means provide a common output node, the output means comprising a plurality of N' resistors each having one terminal connected to the node and the other terminal connected to the output of one of the N' amplifiers.

6. A method of providing low loss amplification substantially as hereinbefore described with reference to the accompanying drawings.

7. A low noise amplifier arrangement substantially as hereinbefore described with reference to the accompanying drawings.

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